Search for New Physics
with $b \rightarrow sll$ decays @ LHCb

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On behalf of the LHCb Collaboration
CERN Seminar, 18th April 2017
A Forward Spectrometer

Optimized for beauty and charm physics at large pseudorapidity ($2 < \eta < 5$)

- **Trigger:** >95% (60-70%) efficient for muons (electrons)
- **Tracking:** $\sigma_p/p$ 0.4–0.6% (p from 5 to 100 GeV), $\sigma_{IP} < 20 \mu m$
- **Calorimeter:** $\sigma_E/E \sim 10\% / \sqrt{E} \oplus 1\%$
- **PID:** ~97% $\mu, e$ ID for 1–3% $p \rightarrow \mu, e$ misID

Analysis presented today based on the full Run 1 dataset.

Due to luminosity levelling, same running conditions throughout fills.

Datasets

LHCb Preliminary 2011+12 data
- Single muon
- Charmonium
- Bottomonium
- Other triggers

Dimuons per GeV/c

Dimuon mass [GeV/c^2]

LHCb-CONF-2016-005
Why Rare $b$ Decays?

- $b \rightarrow s l l$ decays proceed via **FCNC transitions** that only occur at loop order (or beyond) in the SM

- New particles can for example contribute to loop or tree level diagrams by enhancing/suppressing decay rates, introducing new sources of CP violation or modifying the angular distribution of the final-state particles

- Rare $b$ decays place strong constraints on many NP models by probing energy scales higher than direct searches
Differential branching fractions of $B^0 \rightarrow K^{(*)0} \mu \mu$, $B^+ \rightarrow K^{(*)+} \mu \mu$, $B_s \rightarrow \phi \mu \mu$, $B^+ \rightarrow \pi^+ \mu \mu$ and $\Lambda_b \rightarrow \Lambda \mu \mu$

» Presence of hadronic uncertainties in theory predictions

Angular analyses of $B \rightarrow K^{(*)} \mu \mu$, $B_s \rightarrow \phi \mu \mu$, $B^0 \rightarrow K^{*0} \mu \mu$ and $\Lambda_b \rightarrow \Lambda \mu \mu$

» Define observables with smaller theory uncertainties

Test of Lepton Flavour Universality in $B^+ \rightarrow K^+ \ell \ell$ and $B^0 \rightarrow K^{*0} \ell \ell$

» Cancellation of hadronic uncertainties in theory predictions

Different $q^2$ regions probe different processes
In the OPE framework the short-distance contribution is described by Wilson coefficients

$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum \left[C_i O_i + C'_i O'_i \right]$$
Results consistently lower than SM predictions

- $B^+ \rightarrow K^+ \mu^+ \mu^-$
  - LHCb
  - JHEP 06 (2014) 133

- $B_s \rightarrow \phi \mu^+ \mu^-$
  - 3.3σ form SM
  - JHEP 09 (2015) 179

- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
  - LHCb
  - arXiv:1606.04731

- $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$
  - LHCb
  - JHEP 06 (2015) 115
First **full angular analysis** of $B^0 \rightarrow K^* \mu \mu$: measured all CP-averaged angular terms and CP-asymmetries

Can construct **less form-factor dependent ratios of observables**
Once upon a time ...

- LHCb tested Lepton Universality using $B^+ \to K^+ \mu^+ \mu^-$ decays and observed a tension with the SM at $2.6\sigma$

$$\mathcal{R}_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi (\to \mu^+ \mu^-))} / \frac{\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathcal{B}(B^+ \to K^+ J/\psi (\to e^+ e^-))}$$

- Consistent with observed $\text{BR}(B^+ \to K^+ \mu \mu)$ if NP does not couple to electrons
- Observation of LFU violations would be a clear sign of NP

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Several attempts to interpret results by performing global fits to data.

Take into account ~90 observables from different experiments, including $B \to \mu \mu$ and $b \to sll$ transitions.

All global fits require an additional contribution with respect to the SM to accommodate the data, with a preference for NP in $C_9$ at $\sim 4\sigma$.

Or is this a problem with the understanding of QCD? (e.g. correctly estimating the contribution from charm loops?)
Today ...

- Test of LFU with $B^0 \to K^{*0} \mu \mu$ and $B^0 \to K^{*0} ee$, $R_{K^{*0}}$

- **Two regions of $q^2$**
  - Low: [0.045-1.1] GeV$^2$/c$^4$
  - Central: [1.1-6.0] GeV$^2$/c$^4$

- Measured relative to $B^0 \to K^{*0} J/\psi (II)$ in order to reduce systematics
- $K^{*0}$ reconstructed as $K^+ \pi^-$ within 100MeV from the $K^*(892)^0$
- **Blind analysis** to avoid experimental biases

- Extremely challenging due to significant differences in the way $\mu$ and $e$ “interact” with the detector
  - Bremsstrahlung
  - Trigger
Bremsstrahlung – I

- Electrons emit a large amount of bremsstrahlung that results in degraded momentum and mass resolutions

- Two types of bremsstrahlung
  - **Downstream of the magnet**
    - photon energy in the same calorimeter cell as the electron
    - momentum correctly measured
  - **Upstream of the magnet**
    - photon energy in different calorimeter cells than electron
    - momentum evaluated after bremsstrahlung
A recovery procedure is in place to improve the momentum reconstruction.

Events are categorised depending on the number of recovered photon clusters.

In complete recovery due to:

- Energy threshold of the bremsstrahlung photon ($E_T > 75$ MeV)
- Calorimeter acceptance
- Presence of energy deposits mistaken as bremsstrahlung photons

Incomplete recovery causes the reconstructed B mass to shift towards lower values and events to migrate in and out of the $q^2$ bins.
Trigger

› Trigger system split in hardware (Lo) and software (HLT) stages
› Due to higher occupancy of the calorimeters compared to the muon stations, hardware thresholds on the electron $E_T$ are higher than on the muon $p_T$ (Lo Muon, $p_T>1.5,1.8$ GeV)

› To partially mitigate this effect, 3 exclusive trigger categories are defined

  » Lo Electron: electron hardware trigger fired by clusters associated to at least one of the two electrons ($E_T > 2.5$ GeV)

  » Lo Hadron: hadron hardware trigger fired by clusters associated to at least one of the $K^{*0}$ decay products ($E_T > 3.5$ GeV)

  » Lo TIS: any hardware trigger fired by particles in the event not associated to the signal candidate
Strategy

- \( R_{K*0} \) determined as double ratio to reduce systematic effects

\[
R_{K*0} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu^+ \mu^-))} / \frac{\mathcal{B}(B^0 \rightarrow K^{*0} e^+ e^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow e^+ e^-))}
\]

- **Selection as similar as possible between \( \mu \mu \) and ee**
  - Pre-selection requirements on trigger and quality of the candidates
  - Cuts to remove the peaking backgrounds
  - Particle identification to further reduce the background
  - Multivariate classifier to reject the combinatorial background
  - Kinematic requirements to reduce the partially-reconstructed backgrounds
  - Multiple candidates randomly rejected (1-2%)

- **Efficiencies**
  - Determined using simulation, but tuned using data
Corrections to Simulation

› Four-step procedure largely based on tag-and-probe technique

1. **Particle identification**
   » PID response of each particle species tuned using dedicated calibration samples

2. **Generator**
   » Event multiplicity and $B^0$ kinematics matched to data using $B^0 \rightarrow K^{*0} J/\psi(\mu\mu)$ decay

3. **Trigger**
   » Hardware and software trigger responses tuned using $B^0 \rightarrow K^{*0} J/\psi(\ell\ell)$ decays

4. **Data/MC differences**
   » Residual discrepancies in variables entering the MVA reduced using $B^0 \rightarrow K^{*0} J/\psi(\ell\ell)$ decays

› After tuning, very good data/MC agreement in all key observables
Fit Procedure – $\mu\mu$

- Fit signal MC to extract initial parameters
- Simultaneous fit to resonant and non-resonant data allowing (some) parameters to vary

**Signal**
- Hypatia [NIM A, 764, 150 (2014)]
- Free parameters: mass shift and width scale

**Backgrounds**
- Combinatorial: exponential
- $\Lambda_b \rightarrow pK J/\psi(\mu\mu)$: simulation & data
- $B_s \rightarrow K^0 J/\psi(\mu\mu)$: same as signal but shifted by $m_{B_s} - m_{B_0}$ only

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Fit Results – $\mu\mu$

- **low-$q^2$**
  - LHCb Preliminary
  - Signal
  - Combinatorial

- **central-$q^2$**
  - LHCb Preliminary
  - Signal
  - Combinatorial

- **low-$q^2$**
  - LHCb Preliminary
  - Signal
  - Combinatorial
  - $\Lambda_c \rightarrow pK^+ J/\psi$
  - $B_c^- \rightarrow K^{*0} J/\psi$

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Fit Procedure – ee

› Fit signal MC to extract initial parameters
› Simultaneous fit to resonant and non-resonant data split in trigger categories allowing (some) parameters to vary (bremsstrahlung fractions fixed from MC)

› Signal
  » Crystal-Ball (Crystal-Ball and Gaussian)
  » Free parameters mass shift and width scale

› Backgrounds
  » Combinatorial exponential
  » $\Lambda_b \rightarrow p K^* J/\psi (ee)$ simulation & data, constrained using muons
  » $B_s \rightarrow K^0 J/\psi (ee)$ same as signal but shifted by $m_{B_s} - m_{B_0}$, constrained using muons
  » $B^0 \rightarrow K^* J/\psi$ Leakage simulation, yield constrained using data
  » Part-Reco simulation & data

$B^0 \rightarrow K^0 J/\psi$ only

$B^0 \rightarrow K^* J/\psi$ only
Part-Reco Background – 1

- Partially-reconstructed backgrounds arise from decays involving higher $K$ resonances with one or more decay products in addition to a $K\pi$ pair that are not reconstructed.

- Large variety of decays, most abundant due to $B\rightarrow K_1(1270)ee$ and $B\rightarrow K_2^*(1430)ee$. 
Modelled using two independent methods

- Create a $K_1+K_2$ cocktail from simulation and use $B \rightarrow \chi J/\psi (ee)$ data to determine their relative fraction
- Re-weight $B^+ \rightarrow K^+ \pi^+ \pi^- \mu^+ \mu^-$ simulated events using background subtracted $B^+ \rightarrow K^+ \pi^+ \pi^- \mu^+ \mu^-$ data

**Figure:**

- LHCb
- $B^+ \rightarrow K^+ \pi^+ \pi^- \mu^+ \mu^-$

**Source:**

JHEP 10 (2014) 064
Fit Results – ee

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Yields

- Precision of the measurement driven by the statistics of the electron samples

\[
\begin{array}{c|cc|c}
 & B^0 \rightarrow K^{*0} \ell^+ \ell^- & & B^0 \rightarrow K^{*0} J/\psi (\rightarrow \ell^+ \ell^-) \\
 & \text{low-}q^2 & \text{central-}q^2 & \\
\hline
\mu^+ \mu^- & 285 \pm 18 & 353 \pm 21 & \\
e^+e^- (L0E) & 55 \pm 9 & 67 \pm 10 & 43468 \pm 222 \\
e^+e^- (L0H) & 13 \pm 5 & 19 \pm 6 & 3388 \pm 62 \\
e^+e^- (L0I) & 21 \pm 5 & 25 \pm 7 & 11505 \pm 115 \\
\end{array}
\]

- In total, about 90 and 110 $B^0 \rightarrow K^{*0} ee$ candidates at low- and central-$q^2$, respectively
Cross-Checks – I

› Control of the absolute scale of the efficiencies via the ratio

\[ r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^*0 J/\psi \to \mu^+\mu^-)}{\mathcal{B}(B^0 \to K^*0 J/\psi \to e^+e^-)} \]

which is expected to be unity and measured to be

\[ 1.043 \pm 0.006 \text{ (stat)} \pm 0.045 \text{ (syst)} \]

› Result observed to be reasonably flat as a function of the decay kinematics and event multiplicity

› Extremely stringent test, which does not benefit from the cancellation of the experimental systematics provided by the double ratio
Cross-Checks – II

› \( \text{BR}(B^0 \rightarrow K^0 \mu \mu) \) in good agreement with [arXiv:1606.04731]

› If **corrections to simulations** are not accounted for, the ratio of the efficiencies changes by less than 5%

› **Further checks** performed by measuring the following ratios

\[
\mathcal{R}_{\psi(2S)} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0}_{\psi(2S)} (\rightarrow \mu^+ \mu^-))}{\mathcal{B}(B^0 \rightarrow K^{*0}_{J/\psi} (\rightarrow \mu^+ \mu^-))} \left/ \frac{\mathcal{B}(B^0 \rightarrow K^{*0}_{J/\psi} (\rightarrow e^+ e^-))}{\mathcal{B}(B^0 \rightarrow K^{*0}_{J/\psi} (\rightarrow e^+ e^-))}\right.
\]

\[
r_{\gamma} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0}_{\gamma} (\rightarrow e^+ e^-))}{\mathcal{B}(B^0 \rightarrow K^{*0}_{J/\psi} (\rightarrow e^+ e^-))}
\]

which are found to be compatible with the expectations
Cross-Checks – III

› Relative population of *bremsstrahlung categories* compared between data and simulation using $B^0 \rightarrow K^* \gamma J/\psi(\text{ee})$ and $B^0 \rightarrow K^* \gamma (\text{ee})$ events

A good agreement is observed

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Cross-Checks – IV

› The sPlot technique is used to statistically subtract the background from the selected data [NIM A555, 356-369 (2005)]

› A good agreement is observed in both $q^2$ regions between muons and electrons, data and simulation.
No attempt is made to separate the $K^{*0}$ meson from S-wave or other broad contributions present in the mass peak region.

A clear $K^{*0}$ mass peak is visible, and the muon and electron channels manifest a very good agreement.
The opening angle between the two leptons

The distribution is different between muons and electrons at low-$q^2$ because of the difference in the lepton masses.

Even very close to threshold a good description is observed (insert, $0.045 < q^2 < 0.1 \text{ GeV}^2/\text{c}^4$)
R_{K^{*0}} determined as a double ratio

- Many experimental systematic effects cancel
- Statistically dominated (~15%)

<table>
<thead>
<tr>
<th>Trigger category</th>
<th>low-(q^2)</th>
<th>central-(q^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L0E  L0H L0I</td>
<td>L0E  L0H L0I</td>
</tr>
<tr>
<td>Corrections to simulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trigger</td>
<td>2.5  4.8  3.9</td>
<td>2.2  4.2  3.4</td>
</tr>
<tr>
<td>PID</td>
<td>0.1  1.2  0.1</td>
<td>0.2  0.8  0.2</td>
</tr>
<tr>
<td>Kinematic selection</td>
<td>0.2  0.4  0.3</td>
<td>0.2  1.0  0.5</td>
</tr>
<tr>
<td>Residual background</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass fits</td>
<td>2.1  2.1  2.1</td>
<td>2.1  2.1  2.1</td>
</tr>
<tr>
<td>Bin migration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(r_{J/\psi}) flatness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4.0  6.1  5.5</td>
<td>6.4  7.5  6.7</td>
</tr>
</tbody>
</table>

Total systematic uncertainty of 4-6% and 6-8% in the low- and central-\(q^2\)
Systematics – II

› **Corrections to simulation:** besides the uncertainty due to the size of the samples, an additional systematic is determined using different parameterisations of the corrections.

› **Kinematic selection:** a systematic uncertainty for Data/MC differences in the description of the bremsstrahlung tail and the MVA classifier is determined by comparing simulation and background subtracted $B^0 \rightarrow K^{*0} J/\psi(\Pi)$ data.

› **Residual background:** both data and simulation are used to assess a systematic uncertainty for residual background contamination due to $B^0 \rightarrow K^{*0} J/\psi(\Pi)$ events with a $K \leftrightarrow e$ or $\pi \leftrightarrow e$ swap.

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<tr>
<td></td>
<td>LOE</td>
<td>LOH</td>
</tr>
<tr>
<td><strong>Corrections to simulation</strong></td>
<td>2.5</td>
<td>4.8</td>
</tr>
<tr>
<td><strong>Trigger</strong></td>
<td>0.1</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>PID</strong></td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Kinematic selection</strong></td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td><strong>Residual background</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mass fits</strong></td>
<td>1.4</td>
<td>2.1</td>
</tr>
<tr>
<td><strong>Bin migration</strong></td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>$r_{J/\psi}$ flatness</strong></td>
<td>1.6</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>4.0</td>
<td>6.1</td>
</tr>
</tbody>
</table>
Mass fit: a systematic uncertainty is determined by running pseudo-experiments with different descriptions of the signal and background fit models.

Bin migration: the effect of the model dependence and description of the $q^2$ resolution in simulation are assigned as a systematic uncertainty.

$r_{J/\psi}$ flatness: the ratio is studied as a function of several properties of the event and decay products, and the observed residual deviations from unity are used to assign a systematic uncertainty.

<table>
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<tr>
<td>Corrections to simulation</td>
<td>2.5</td>
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<td>3.9</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.1</td>
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<td>2.1</td>
<td>2.5</td>
</tr>
<tr>
<td>Bin migration</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$r_{J/\psi}$ flatness</td>
<td>1.6</td>
<td>1.4</td>
<td>1.7</td>
</tr>
<tr>
<td>Total</td>
<td>4.0</td>
<td>6.1</td>
<td>5.5</td>
</tr>
</tbody>
</table>
The measured values of $R_{K^{*0}}$ are found to be in good agreement among the three trigger categories in both $q^2$ regions.
The compatibility of the result in the low-$q^2$ with respect to the SM prediction(s) is of 2.2-2.4 standard deviations.

The compatibility of the result in the central-$q^2$ with respect to the SM prediction(s) is of 2.4-2.5 standard deviations.
Using the full Run 1 data set the $R_{K^{*0}}$ ratio has been measured by LHCb with the best precision to date in two $q^2$ bins.

The compatibility of the result with respect to the SM prediction(s) is of 2.2-2.5 standard deviations in each $q^2$ bin.

The result is particularly interesting given a similar behaviour in $R_K$.

Rare decays will largely benefit from the increase of energy (cross-section) and collected data (~5 fb$^{-1}$ expected in LHCb) in Run 2.

LHCb has a wide programme of LU tests based on similar ratios.

Future measurements will be able to clarify whether the tantalising hints we are observing are a glimpse of NP.
Backup
Calorimeter System

- Composed of a Scintillating Pad Detector (SPD), a Preshower (PS), an electromagnetic calorimeter (ECAL) and a hadronic calorimeter (HCAL)
- The SPD and the PS consist of a plane of scintillator tiles (2.5 radiation lengths, but to only \( \sim 6\% \) hadronic interaction lengths)
- The ECAL has shashlik-type construction, i.e. a stack of alternating slices of lead absorber and scintillator (25 radiation lengths)
- The HCAL is a sampling device made from iron and scintillator tiles being orientated parallel to the beam axis (5.6 interaction lengths)
Relative population of bremsstrahlung categories compared between data and simulation using $B^0 \to K^{*0} J/\psi (ee)$ and $B^0 \to K^{*0} \gamma (ee)$ events.

Table 6: Fraction of simulated $B^0 \to K^{*0} J/\psi (\rightarrow e^+e^-)$ and $B^0 \to K^{*0} \gamma (\rightarrow e^+e^-)$ events (in percent) with 0, 1 and 2 recovered photons per trigger category. The number in brackets is determined on data. For $B^0 \to K^{*0} \gamma (\rightarrow e^+e^-)$, due to the very low opening angle of the two electrons, it is not possible to assign unambiguously one photon to a track.

<table>
<thead>
<tr>
<th>Trigger category</th>
<th>0γ</th>
<th>1γ</th>
<th>2γ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$B^0 \to K^{*0} J/\psi (\rightarrow e^+e^-)$</td>
<td>$B^0 \to K^{*0} \gamma (\rightarrow e^+e^-)$</td>
<td>$B^0 \to K^{*0} \gamma (\rightarrow e^+e^-)$</td>
</tr>
<tr>
<td>L0E</td>
<td>27.7 ± 0.2 (26.6 ± 0.2)</td>
<td>49.7 ± 0.2 (50.0 ± 0.2)</td>
<td>22.6 ± 0.2 (23.4 ± 0.2)</td>
</tr>
<tr>
<td>L0H</td>
<td>16.7 ± 0.6 (15.1 ± 0.6)</td>
<td>49.5 ± 0.8 (50.4 ± 0.8)</td>
<td>33.8 ± 0.8 (34.6 ± 0.7)</td>
</tr>
<tr>
<td>L0I</td>
<td>22.4 ± 0.4 (21.4 ± 0.4)</td>
<td>50.2 ± 0.5 (50.4 ± 0.5)</td>
<td>27.2 ± 0.4 (28.3 ± 0.4)</td>
</tr>
</tbody>
</table>

A good agreement is observed.
The distance between the $K\pi$ and $\ell\ell$ vertices

The hadron and lepton pairs consistently originate from the same decay vertex
Results – III

What about NP?

\[ \mathcal{R}_{K^0} \]

\[ q^2 \text{ [GeV}^2/c^4] \]

- LHCb
- CDHMV: \( C_{9\mu}^{NP} = -1.1 \)
- CDHMV: \( C_{9\mu}^{NP} = -C_{10\mu}^{NP} = -0.65 \)
- CDHMV: \( C_{9\mu}^{NP} = -C_{10\mu}^{NP} = -1.07 \)
- CDHMV: \( C_{9\mu}^{NP} = -C_{10\mu}^{NP} = -1.18 \) and \( C_{10\mu}^{NP} = C_{10\mu}^{NP} = 0.38 \)
- EOS: benchmark point \( C_{9\mu}^{NP} = -1.0 \)
- EOS: data driven \( C_{9\mu}^{NP} \) from \( P' \) and \( R_K \)
- flav.io: \( C_{9\mu}^{NP} = -1.1 \)
- flav.io: \( C_{9\mu}^{NP} = -C_{10\mu}^{NP} = -0.65 \)
Di-Lepton Mass

Photon pole enhancement (doesn’t exist for $B \rightarrow P \ell \ell$ decays)

$J/\psi(1S')$

$\psi(2S')$

$b \rightarrow c\bar{c}s$ tree level (!)

$C_7^{(i)}$ and $C_9^{(i)}$

Long distance contributions from $c\bar{c}$ above open charm threshold

$C_9^{(i)}$ and $C_{10}^{(i)}$

$4[m(\mu)]^2$

$\frac{d\Gamma}{dq^2}$

removed from analysis

$q^2$

dimuon mass squared
Theoretical Framework

- In the Fermi model of the weak interaction, the full electroweak Lagrangian (which was unknown at the time) is replaced by the low-energy theory (QED) plus a single operator with an effective coupling constant.

\[ \mathcal{L}_{\text{EW}} \rightarrow \mathcal{L}_{\text{QED}} + \frac{G_F}{\sqrt{2}} (\bar{u}d)(e\bar{\nu}) \]

- Can write a Hamiltonian for the effective theory as

\[ \mathcal{H}_{\text{eff}} = -\frac{4}{\sqrt{2}} G_F V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i C_i(\mu) O_i(\mu), \]

- Wilson coefficient (integrating out scales above \( \mu \))

- Local operator with different Lorentz structure (vector, axial vector current etc)
Operators

SM operators

\[ \mathcal{O}_7 = \sigma^{\mu\nu} F_{\mu\nu}, \]
\[ \mathcal{O}_8 = g_s \sigma^{\mu\nu} P_R T^a b G_{\mu\nu}^a, \]
\[ \mathcal{O}_9 = \gamma_{\mu} P_L b \bar{\ell} \gamma_{\mu} \ell, \]
\[ \mathcal{O}_{10} = \gamma_{\mu} P_L b \bar{\ell} \gamma_{\mu} \gamma_5 \ell. \]

Beyond SM operators

\[ \mathcal{O}_7' = \sigma^{\mu\nu} F_{\mu\nu}, \]
\[ \mathcal{O}_8' = g_s \sigma^{\mu\nu} P_L T^a b G_{\mu\nu}^a, \]
\[ \mathcal{O}_9' = \gamma_{\mu} P_R b \bar{\ell} \gamma_{\mu} \ell, \]
\[ \mathcal{O}_{10}' = \gamma_{\mu} P_R b \bar{\ell} \gamma_{\mu} \gamma_5 \ell. \]

Right handed currents (suppressed in SM)
Angular Analyses

- Complex angular distribution:

\[
\left. \frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\Omega} \right|_P = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \right. \\
\left. + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_l \\
- F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi \\
+ S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi \\
\left. + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi \\
+ S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right]
\]

The observables depend on form-factors for the \( B \to K^* \) transition plus the underlying short distance physics (Wilson coefficients).
Interpretation of Global Fits

Optimist’s view point

Vector-like contribution could come from new tree level contribution from a $Z'$ with a mass of a few TeV

Pessimist’s view point

Vector-like contribution could point to a problem with our understanding of QCD, e.g. are we correctly estimating the contribution for charm loops that produce dimuon pairs via a virtual photon.

More work needed from experiment/theory to disentangle the two
Interpretation of Global Fits

- This is the physics we are interested in.

- We also get long-distance hadronic contributions. Included in the SM but are the predictions correct?

Short distance part integrates out (as a Wilson coefficient)